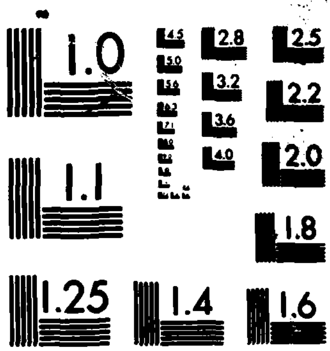
AD-A166 169 RESEARCH ON NONLINEAR CONTROL THEORY(U) JOHNS HOPKINS UNIV BALTIMORE MD DEPT OF ELECTRICAL ENGINEERING AND CCOMPUTER SCIENCE W J RUGH MAR 84 AFOSR-TR-86-0043 1/1
UNCLASSIFIED AFOSR-83-0079 F/G 9/3 NL



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SECURITY CLASSIFICATION OF THIS PAGE

(2)

AD-A166 169

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified AD-A166169

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S):

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 86-0043

6a. NAME OF PERFORMING ORGANIZATION: The Johns Hopkins University Dept. of Elect. Engr. & Comp. Sci.

6b. OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION: Air Force Office of Scientific Research

6c. ADDRESS (City, State and ZIP Code): Baltimore, Maryland 21218

7b. ADDRESS (City, State and ZIP Code): Bolling AFB, Washington, D.C. 20332

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR

8b. OFFICE SYMBOL (If applicable): NM

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-83-0079

8c. ADDRESS (City, State and ZIP Code): Bldg. 410, Bolling AFB, D.C. 20332-6448

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2304	A1	

11. TITLE (Include Security Classification): RESEARCH ON NONLINEAR CONTROL THEORY

12. PERSONAL AUTHOR(S): Rugh, Wilson J.

13a. TYPE OF REPORT: Annual

13b. TIME COVERED: FROM 3/1/84 TO 2/28/85

14. DATE OF REPORT (Yr., Mo., Day): 1984 March

15. PAGE COUNT: 4

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Control Theory, Nonlinear Systems, Volterra Series

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This annual report briefly describes progress on research in nonlinear control theory. Results reported include the formulation of a new approach, called design by extended linearization, for the design of nonlinear feedback (state, or output) control laws for nonlinear systems. This approach can be based on the Volterra series input-output representation, or, more generally, on the state equation representation of the system to be controlled. The design yields a closed-loop system whose linearizations about constant operating points have specified eigenvalues. Publications describing the results in detail are listed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr. Marc Q. Jacobs

22b. TELEPHONE NUMBER (Include Area Code): (202)-767-4940

22c. OFFICE SYMBOL:

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

86 4 1 032

AFOSR-TR- 86-0043

RESEARCH ON NONLINEAR CONTROL THEORY

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ANNUAL SCIENTIFIC REPORT

under

Grant Number AFOSR-83-0079

for the period

1 March 1984 through 28 February 1985

ABSTRACT

This annual report briefly describes progress on research in nonlinear control theory. Results reported include the formulation of a new approach, called design by extended linearization, for the design of nonlinear feedback (state, or output) control laws for nonlinear systems. This approach can be based on the Volterra series input-output representation, or, more generally, on the state equation representation of the system to be controlled. The design yields a closed-loop system whose linearizations about constant operating points have specified eigenvalues. Publications describing the results in detail are listed.

1. RESEARCH OBJECTIVES AND STATUS

The objective of this research effort involves the use of recent developments in the representation and realization theories for nonlinear systems to address the problem of nonlinear feedback control. In particular, the objective is to develop more effective analysis and design techniques for nonlinear control systems.

Based on our earlier work characterizing the family of linearized systems associated to a given nonlinear system, [1], [2], [3]*, we have developed a new approach to nonlinear control system design that we call 'design by extended linearization.' [5], [6], [7] The basic idea behind this approach can be described briefly as follows.

A standard approach to design of nonlinear systems involves linearizing the system about a nominal constant operating point (equilibrium point), and applying linear design techniques. This yields a linear control law, and a nonlinear closed-loop system whose linearization about the nominal constant operating point has specified properties, for example, eigenvalue locations. If the closed-loop system is operated in a neighborhood of the nominal operating point, it should exhibit the behavior of its linearization. The difficulty, of course, is that it usually is desired to control a nonlinear system over a wide range of operation, so this approach breaks down. Sometimes ad-hoc gain scheduling is used, where parameters in the linear control law are adjusted corresponding to some measure of the current operating region of the system.

Our approach is to extend the notion of design based on linearization in the following way. Suppose that the system to be controlled has a family of constant operating points, parameterized by constant input values. Then we can consider the corresponding parameterized family of linearized systems, and, for example, easily compute a family of linear state feedback gains that places the eigenvalues at specified values independent of the parameter. Finally, and this is the novel feature of the approach, this family of linear gains is 'realized' by a nonlinear state feedback gain. That is, a nonlinear gain can be computed whose family of linearizations, corresponding to the closed-loop operating point, is precisely the designed family of linear gains. Thus, so long as the region of operation of the nonlinear system remains in a neighborhood of any constant operating point in the family, it should exhibit the specified behavior.

A similar approach can be taken to the design of state observers, where nonlinear observer gains are computed such that the family of linearized error equations has specified eigenvalues. Then it is not hard to show that output feedback through the nonlinear observer can be used to achieve eigenvalue placement for the closed-loop linearization family. This appears to be the first general approach to the design of nonlinear output feedback control laws to have appeared.

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* Numbers in square brackets refer to publications listed in Section 2 of this report.

The basic idea of design by extended linearization was introduced in terms of Volterra series representations in [5]. Subsequent papers have focused on the more general formulation provided by state equation representations. The single-input case is discussed in [6], along with a study of the performance of the method as applied to the classical problem of automatically balancing an inverted pendulum. The basic theory for the multi-input case, which is technically more difficult, is essentially completed, and a paper is in preparation. [7]

In parallel with these theoretical developments, and with the consultation of personnel at Wright-Patterson AFB, application of this approach to a nonlinear (4-state, pitch axis) flight control model is proceeding. We recently have confirmed that the method is not difficult to apply to this example, and current work is focusing on the attainment of flying-quality criteria at high angles of attack, and on stall recovery issues.

Progress in our efforts to develop a better nonlinear system simulation/computation facility should be noted. This is crucial for applying (and demonstrating the effectiveness of) our results on nontrivial problems. In designing a control law for the flight control model mentioned above, extensive use has been made of the symbolic computation language MACSYMA that we recently acquired. Simulation of the performance of the system is carried out on CSMP (Continuous System Modeling Program), although efforts are being made to acquire a more efficient program with better graphics capabilities.

2. PUBLICATIONS

(Cumulative, from 1 March 1983.)

[1] R. Lejeune and W. J. Rugh, "Linearization of Discrete-Time Polynomial Systems About Constant Operating Points," Proceedings of the 17th Annual Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore, MD, pp. 422-426, 1983.

[2] W. J. Rugh, "Linearization About Constant Operating Points: An Input-Output Viewpoint," Proceedings of the 22nd IEEE Conference on Decision and Control, San Antonio, TX, pp. 1165-1169, 1983.

[3] R. Lejeune and W. J. Rugh, "Linearization of Nonlinear Systems About Constant Operating Points," IEEE Transactions on Automatic Control, to appear, June, 1984.

[4] W. J. Rugh, "An Input-Output Characterization for Linearization by Feedback," Systems and Control Letters, Vol. 4, No. 4, pp. 227-229, June, 1984.

[5] W. J. Rugh, "Design of Nonlinear Compensators for Nonlinear Systems by an Extended Linearization Technique," Proceedings of the Twenty-Third IEEE Conference on Decision and Control, Las Vegas, NV, pp. 69-73, December 1984.

[6] W. T. Baumann and W. J. Rugh, "Feedback Control of Nonlinear Systems by Extended Linearization," submitted to IEEE Transactions on Automatic Control, 1984.

[7] W. T. Baumann and W. J. Rugh, "Feedback Control of Nonlinear Systems by Extended Linearization: The Multi-Input Case," accepted for publication, Proceedings of the Seventh International Symposium on the Mathematical Theory of Networks and Systems, 1985.

3. PERSONNEL

Principal Investigator: Wilson J. Rugh

Research Assistants (Graduate Students):

William T. Baumann: BS, Lehigh University; MS, M.I.T.

Jian-Liang Wang: BS, Beijing Institute of Technology; MS completed, December, 1984, Johns Hopkins University

Judith E. Blank: BA, University of Chicago

4. INTERACTIONS

Presentations of the publications in Section 2 during the period 1 March 1984 - 28 February 1985 were as follows.

[4] was presented at the Conference on Information Sciences and Systems, Princeton, NJ, on 15 March 1984.

[5] was presented at a research seminar, IBM Watson Research Center, Yorktown Heights, NY, on 12 July 1984; and at the IEEE Conference on Decision and Control, Las Vegas, NV, on 12 December 1984.

[6] was presented at a research seminar in the Department of Electrical Engineering and Computer Science, Princeton University, Princeton, NJ, on 25 September 1984; and will be presented at the Conference on Information Sciences and Systems, Baltimore, MD, on 28 March 1985.

[7] will be presented at the Seventh Annual Symposium on the Mathematical Theory of Networks and Systems, Stockholm, Sweden, June, 1985.

In addition, W. J. Rugh visited Wright-Patterson AFB, Ohio, on 23 January 1985, where he met with Mr. Charles Suchomel, and others, of AFWAL/FIGC, and Professors D'Azzo, Houpis, Jones, and others, of AFIT. The subject of this visit was a nonlinear flight control model to be used as a test case for the application of the extended-linearization design method discussed in Section 1. Interaction is continuing as work on the application proceeds.

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